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Synergy Analysis Methodology For Decreasing Fuel Cell Production Costs

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Abstract

For meeting CO2 emission targets in the mobility sector, decarbonization efforts of referring applications are necessary. Fuel Cell electric vehicles powered by hydrogen demonstrate a viable option to achieve those targets, especially taking the targets of heavy-duty applications into consideration. Higher ranges, short fueling durations and locally emission-free transport represent advantages offered by Fuel Cells in comparison to internal combustion engines or battery-electric powertrains.

However, production costs of Fuel Cells are still a major drawback. Latest analyses show that the utilization of scale effects even in early technology adaption phases can heavily decrease production costs. As the cell structure of Fuel Cells and Electrolyzers show many similarities, the assumption of production synergies is made. Taking advantage of referring synergies, increased production volumes and thus decreased production costs are assumed for both, Fuel Cells and Electrolyzers.

This paper introduces a methodology to identify synergies between Fuel Cell and Electrolyzer production. The methodology is used to evaluate a company's production process portfolio on the example of the three alternative coating processes and a target product, based on an initial evaluation of the processes and the use of the Analytic Network Process. The application of the methodology results in synergy coefficients for production processes, using the exemplary portfolio consisting of slot die, gravure and spray coating. The coefficients are transferred into an overall benefit of a production process portfolio. Finally, the effect of the considered synergies between Fuel Cell and Electrolyzer production on the overall benefit of a company's production process portfolio is visualized. This paper is concluded with a critical review of the methodology and a summary of further research.

Keywords

Fuel Cell; Fuel Cell Production; Electrolyzer; Production Costs; Synergy Analysis; Economies of Scale; Production Process Portfolio; Analytic Network Process; Coating Process

1. Introduction

To address the climate crisis, a large number of comprehensive challenges need to be solved to prevent irreversible damage to the climate system. Consequently, it is essential to reduce CO2 emissions in all sectors as these are directly related to climate change [1]. In order to reduce the emissions in the transport sector, the main aim is to increase the percentage of electric driven vehicles, especially in heavy road and freight transport. To achieve this, various alternative drive systems are currently being researched.[2] Polymer-Electrolyte-Membrane (PEM) Fuel Cell (FC) electric driven vehicles and hydrogen as an alternative fuel promise high potential. Due to short refueling durations, long ranges and locally CO2 neutrality, the PEMFC

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is a potential complement to conventional battery electric driven vehicles, that are indispensable in the passenger car segment and lower loads. This will expand the variety of electric vehicles and take a step towards a CO2 neutral heavy road and freight transport.[3]

For increasing Fuel Cell electric vehicle (FCEV) competitiveness compared to conventional Internal Combustion Engine (ICE) vehicles, investment costs must be reduced. FCEVs are up to 60% more expensive than diesel vehicles, with about 35% of the costs being determined by the Fuel Cell system. Another cost factor is hydrogen as the fuel for the alternative powertrain.[4] Hydrogen fuel is currently up to 90% more expensive than conventional fuels which is partly due to the production costs of the PEM Electrolyzer (EL) components [4]. Due to the largely identical design of PEMFC and PEMEL cells, synergies are assumed to exist in particular in the production processes. This paper is focussing the hypothesis that the exploitation of synergies results in a sustainable reduction of PEMFC and PEMEL production costs especially in early technology adaption phases. Thus, a methodology is developed to identify and examine synergies between the production processes in order to prioritize the utilization of different production processes of PEMFC and PEMEL.

2. Objectives and state of the art

2.1 Introduction in the field of electrochemical energy converters

PEMFC and PEMEL are assigned to the electrochemical energy converters that either use hydrogen and oxygen to produce electricity nor water and electricity to produce hydrogen. Basically, different types of PEMFC and PEMEL exist, whereby the used electrolyte, operation temperature and the conducted ions are the main criteria to divide PEMFC in seven and PEMEL in three categories.[5] Although each type has its advantages, PEM technology is considered to have the highest future potential in terms of variety in applications and robustness in operation for both, PEMFC and PEMEL.[6] The main field of application for PEMFC is the automotive sector due to their potential for dynamic operation strategies as well as their lower operating temperatures compared to other Fuel Cell technologies. Furthermore, PEMFC are able to be used in the field of stationary power generation. PEMEL also show advantages to other Electrolyzer technologies, especially due to its higher efficiency and the ability to take up huge overloads. The latter will become more important, as future energy systems will be operated in a more dynamic manner due to the use of volatile energy sources.[3] Thus, this paper focuses on PEM technologies.

2.2 State of the art of PEMFC and PEMEL cell architecture

In Figure 1, the typical structure of a PEMFC and PEMEL with their main functional layers is shown. A polymeric membrane represents the core of a PEMFC. This membrane is used to transport protons between the anode and the cathode and to separate the reaction chambers of the cell from each other.[6] To accelerate the dissociation process of hydrogen and oxygen, a catalyst layer (CL) is applied to the membrane [7]. The CL usually consists of a platinum-based catalyst, ionomer and a carbon support to further increase the electrochemical surface area and forms the electrode [8]. Both, PEM and CL, yield the Catalyst Coated Membrane (CCM) [9]. The gas diffusion layer (GDL) is attached on both sides to the CCM, contributes to a homogeneous distribution of the reaction gases over the entire cross section of the electrodes active area and conducts the charge carriers [7], [10]. A micro porous layer (MPL) is applied to the GDL and improves water management in the whole system [11]. CCM and GDL represent the Membrane-Electrode-Assembly (MEA). As one single PEMFC produces one voltage, multiple cells need to be stacked and electrically connected in series. Therefore, Bipolar plates (BPP) finalize the package and mainly take responsibility for electrical contacting the various cells, provide mechanical stability and feed the cells with the product gases. [6]

The assembly of an PEMEL cell is comparably similar to PEMFC. Nevertheless, several differences can be observed mainly at anode side of a PEMEL cell as a chemical potential of up to two volts is prevailed. Thus, titanium is used for the BPP, layered expanded metals of titanium form the Porous Transport Layer (PTL), which is the counterpart of the PEMFC GDL and iridium oxide is used as the catalyst. Furthermore, the membrane in PEMELs is thicker than in the PEMFC as operating with differential pressures of up to 50 bar(a) improves hydrogen storage efficiency, but doesn't differ in material or structure.[6], [12]

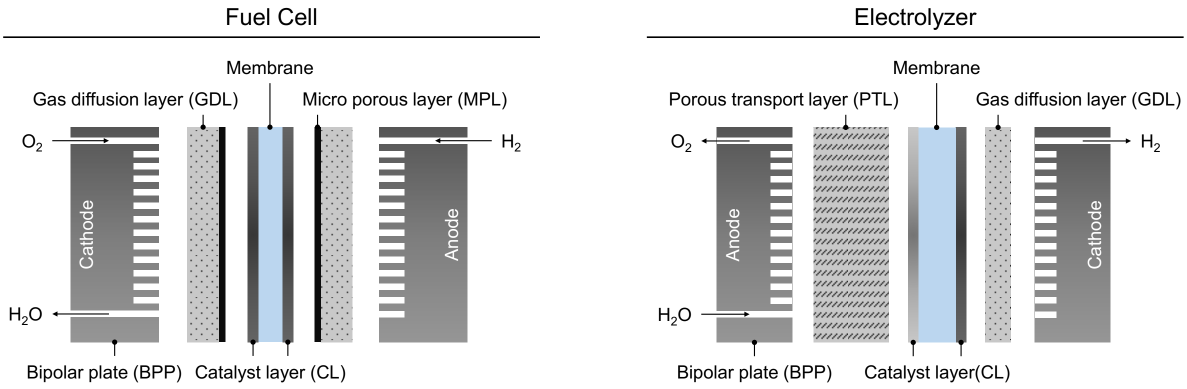

Figure 1: Product architecture of PEMFC and PEMEL [6], [13]

The similarities described between the two cell architectures suggest that there are synergies between the two products that can be exploited. Therefore, the production processes need to be examined in order to confirm this assumption.

2.3 State of the art of PEMFC and PEMEL catalyst coating

Catalyst coating processes for PEMFC and PEMEL do not greatly differ between the two technologies and are still accompanied by several challenges against the background of a high-volume production (Figure 2). In order to demonstrate the method presented later, three processes that are usually used in small- to large-scale production environments will be described more in detail: Spray, slot die and gravure coating.

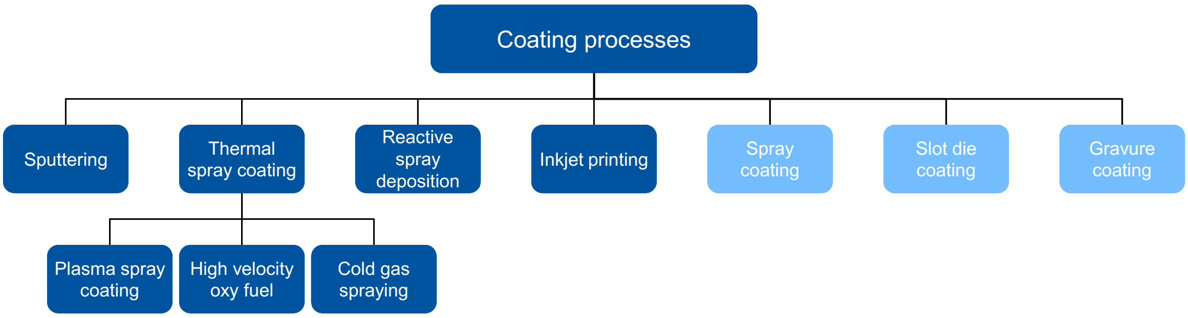

Figure 2: Overview coating processes for electrochemical energy converters [14], [15], [16], [17], [18], [19], [20], [21], [22]

In the three processes, the CL can either be applied in a direct manner to the membrane or GDL, or in an indirect manner to a transfer Decal foil. A Decal foil is a PTFE-based foil, that is used in combination with an additional hot press process to transfer the CL to the membrane or GDL. In case, the CL is applied to the membrane, the final product type is the CCM; at the GDL, the product is called GDE.[23]

In spray coating, the CL is built up layer by layer by multiple pre-defined spraying paths, that allows high homogeneity and precise adjustment of the catalyst loading [24]. Due to the layered structure, the process is usually used for small series production and is characterized by a higher production duration [24,25]

In slot die coating, the catalyst is applied through a slot die in a continuous roll-to-roll process. The layer thickness of the CL is adjusted by the gap between the slot die and the substrate.[15] By aligning the substrate vertically, its both sides can be coated simultaneously. This saves installation space in the coating machine but is only conceivable when direct coating the membrane.[26]

In (roto-)gravure coating, the catalyst ink is applied to the substrate by a roller with incorporated structures in a continuously manner. Due to its viscosity, the ink adheres to the structures and is then applied to the substrate. The thickness of the CL is adjusted by the relative speed difference between the roller and the substrate, by varying the incorporated structures of the roller, and by the properties of the catalyst ink (Figure 3).[16]

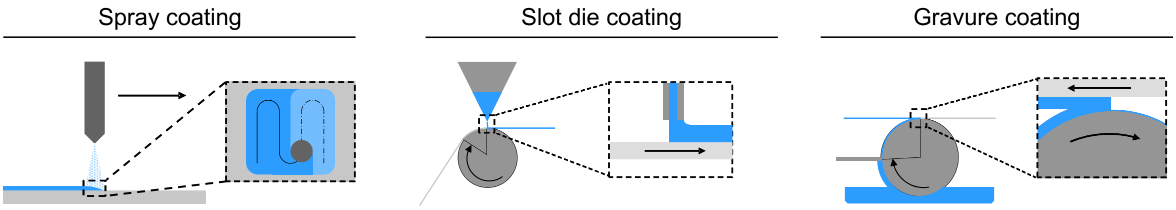

Figure 3: Process details spray coating, slot die coating and gravure coating [14], [27], [28]

2.1 Methodological approaches already existing

The Analytic Network Process (ANP) approach according to SAATY is considered for a multi-criteria evaluation of quantitative and qualitative characteristics through an individual assessment of objectives, target criteria and components. The approach according to LI ET AL. is considered for synergy identification according to the ANP procedure. The general definition of synergies according to WÖGINGER is described as well and its proposed positive and negative synergy categories. In general, synergies can be defined as the effect of increasing the benefit of a totality of sub-elements compared to the sum of the benefits of the individual sub-elements on its own. In this paper, in comparison to positive synergies, negative synergies can occur when the sum of the individual benefits exceeds the total benefit. Positive synergies usually have to be actively pursued in order to occur. Negative synergies, on the other hand, occur undesirably and unplanned.[29]

2.1.1 Analytic Network Process according to SAATY

In the ANP according to SAATY, the objectives, target criteria and components are compared in pairs to form a control component. From the pairwise comparisons, prioritization vectors are generated. Individual prioritization vectors are collected in a supermatrix. Apart from the direct influences of the components to each other, also indirect influences between components exist. Such indirect influences are developed by the direct influence on a third component, which itself interacts again with one of other components. These indirect chained influences are then combined with the supermatrix to form the boundary matrix. Prioritization factors of the considered components are calculated taking the indirect influences of the components to each other into account. This consideration is likewise applicable under the target criteria and objectives, if dependencies exist. SAATY additionally introduces an inconsistency ratio in order to detect inconsistencies in the individual pairwise comparisons. [30]

2.1.2 Synergy Identification approach according to LI ET AL.

An approach for synergy investigation based on the ANP is presented by LI ET AL. The methodology is used to identify the best combination of individual processes considering the synergies among them. For this purpose, the processes are first evaluated in the categories of cost, quality, time, service, resource consumption and environmental impact. Following, the processes are referred to as components. The categories are weighted relative to each other and for a quantitative evaluation, subcategories are assigned to each of these categories. The subcategories within a category are weighted likewise relative to one another. Subsequently, a value from zero as “very poor” to ten as “very good” is assigned to the considered component. The evaluation results in the direct benefit of the respective components.[31]

The components are following compared with each other using the ANP according to Saaty. For this, the components are compared with each other to maximize the total benefit as the overall target. Further, the individual components are compared to the control component pairwise with one another to form the supermatrix and further computing the boundary matrix. The values of the boundary matrix are defined as synergy coefficients, which need to be offset with the ratios for the direct benefit of a component portfolio to calculate its total benefit. [31]

2.1.3 Synergy Definition according to Wöginger

According to Wöginger, positive and negative synergies exist, which will be further considered in the Synergy Analysis methodology. Positive synergies are represented by knowledge transfer between two production processes. This effect occurs, when a company has different product programs that have similarities in process parameters, resources and capabilities. Furthermore, economies of scale occur with an increased output quantity of a product, which is accompanied by cost reduction per unit. Wöginger additionally classifies synergies that increase the company's sales and market power through the development of new markets or the expansion of the product range as growth synergies. Diseconomies of scales represent negative synergies and occur, when the output quantity is increased above a company-specific optimum and thus results in cost increase per unit. After describing different types of synergies, Wöginger introduces the realization probability as an additional factor. The probabilities range from 100% for “expected” to 10% for “hypothetical” realization probability.[29]

2.1.4 Comparison of the presented approaches existing in the literature

In order to evaluate the presented approaches, a set of requirements has to be defined. First of all, the coverage of a given data basis is needed in a detailed and structured manner by the approaches. Another requirement is the general applicability of an approach on a predefined scope. Additionally, the utilization of an approach to analyze quantitative as well as qualitative criteria has to be ensured. As a final requirement, the approach should provide a guideline for classifying and identifying positive and negative synergies. The evaluation of the previously introduced approaches is illustrated in Figure 4.

Evaluation criteria	Approach according to Li et al.	Approach according to Wöginger
Coverage of a given data basis	✓	O
General applicability	✓	—
Qualitative and quantitative analysis	O	O
Classifying and identifying synergies	—	O

✓ Fulfilled   O Partially fulfilled   — Not fulfilled

Figure 4: Comparison and evaluation of existing literature approaches for synergy analysis [31], [29]

The method according to Li et al. combines a comprehensive qualitative evaluation of different components. As a result, a value for the total benefit of the component portfolio is given, which enables the comparability of different portfolios. In addition, the approach provides a detailed and structured coverage of a given data base. Likewise, the method allows a general applicability, which makes a reformulation to application-specific considerations possible. However, only the qualitative evaluation of the methods is presented and the implementation of quantitative features is not further discussed. Furthermore, no guideline for synergetic classification and synergy identification is described. [29]

The method according to WÖGINGER offers a detailed elaboration of the synergy definitions and considerations. Thus, it provides a mature definition framework that can be used to guide the formulation of application-specific synergies. However, the method requires detailed quantified data and only cost factors are included in the evaluation. Thus, a methodology for quantifying qualitative characteristics has to be developed beforehand.[31]

Taking these results into account, a methodology to systematically consider and evaluate synergies in production processes and referring company process portfolios has to be conceptualised. Furthermore, the influence of individual synergies on the total benefit of company's production process portfolio has to be analysed.

3. Methodological concept

3.1 General structure of the methodology

The objective of the methodology is to maximize the benefit of a portfolio of components. Following, the methodology will be enhanced by a dedicated synergy analysis. To evaluate the portfolios, the benefits of the individual components are first assessed. Subsequently, synergies are identified and coefficients of the components are determined. The synergy coefficients and the direct benefit of the components are used to calculate the total benefit of a portfolio of components (Figure 5).

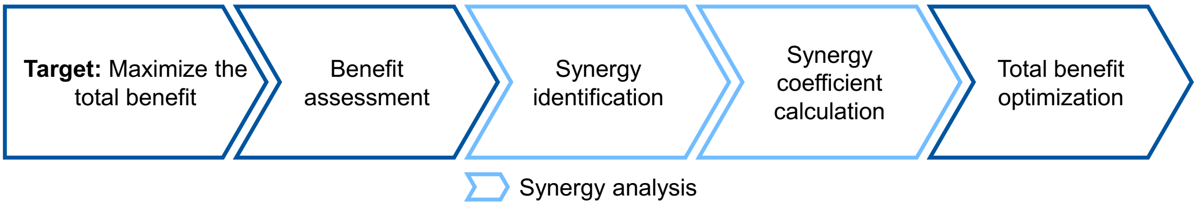

Figure 5: General structure of the methodology for benefit optimization enhanced by synergy analysis steps

3.2 Objective

The objective of the methodology is to maximize the total benefit of a portfolio of components. This objective assumes, that not every component is selected for the portfolio from an existing number of components. Accordingly, the best combination of components has to be identified so that the overall benefit of the portfolio is maximized.

3.3 Benefit assessment

In the benefit assessment, the categories and subcategories are defined and weighted. An ANP approach is used in order to compare more than two categories to each other and minimize inconsistencies. A "zero" to "nine" scale is used to evaluate the components following a standardization towards the best value within the scale. The direct benefit of a component is calculated according to LI ET AL (see Formula 1) [31].

$$u_n = \sum_{p=1}^{P} d_p \sum_{m=1}^{M_p} c_{pm} u_{npm} \tag{1}$$

In Formula 1, u_n defines the direct benefit, P defines the number of categories, d_p defines the weighting of the category p, M_p defines the number of subcategories of the category p, c_{pm} defines the weighting of the subcategory m of the category p and u_{npm} defines the evaluation of the component n in the subcategory m of the category p.

3.4 Synergy identification

In order to identify synergies between individual components, an identification process is performed for each component (see Figure 6). Therefore, each component is considered once as an identification component to determine the synergies of the other components to that identification component. Subsequently, the synergies are quantified by taking referring realization probabilities into account. The result are synergy values of the individual components to an identification component which is represented in Figure 6.

3.5 Synergy coefficient calculation

To calculate synergy coefficients, the approach of LI ET AL. is conducted based on an ANP approach. For this purpose, the synergy values and the direct benefit values are used. In an initial comparison matrix, the components are compared to the control component of the direct benefit. Subsequently, the components to be considered are listed once each as control components. The remaining components are then compared in their synergy count values to the control component in pairs. The prioritization vectors of the different comparison matrices are collected in a supermatrix and the boundary matrix is calculated. The row entries of the boundary matrix form the synergy coefficients of the components of the respective row. The synergy coefficients describe in their height the number of synergies to the other components (Figure 6). Within the example illustrated in Figure 6, the Decal Fuel Cell approach shows the highest synergy coefficient and thus the highest synergy in total compared to the other two production approaches itself.

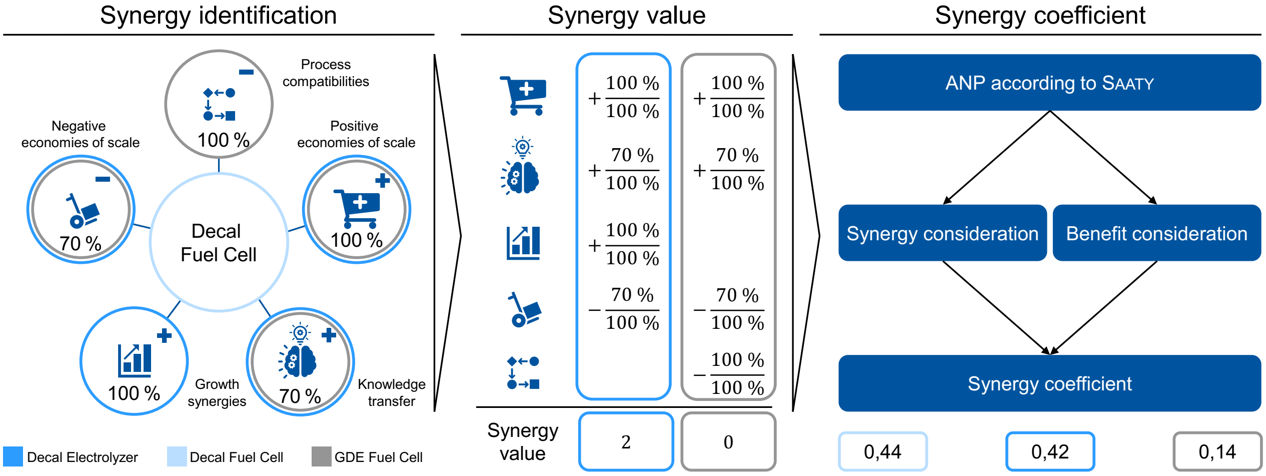

Figure 6: Synergy Analysis steps of the methodology

3.6 Total benefit optimization

The total benefit of a component portfolio is calculated according to LI ET AL. and is illustrated in Formula (2) [31]. For this purpose, the direct benefits of the individual components are set against the referring synergy coefficient.

$$U = \sum_{n=1}^{N} u_n(1 + s_n) \tag{2}$$

In Formula (2), U defines the total benefit of a portfolio, N defines the number of components in a portfolio, u_n defines the direct benefit of component n and s_n defines the synergy coefficient of component n.

4. Model application

4.1 Use case definition

The methodology is applied to a use case in which production process portfolios of spray, slot die and gravure coating are investigated. Therefore, the coating processes in the three possible coating concepts CCM, GDE and Decal transfer are being investigated. In this use case, the Decal transfer considers only the application to the membrane (Decal (CCM)). In addition, the expansion of the product portfolio to the production of PEMEL applications is also being considered.

Based on the state of the art of coating processes, for spray coating 75 nozzles are connected in series and 160 layers are assumed for the CL. For slot die coating, double-sided coating across the full width of the substrate is assumed. For gravure coating, only a single-sided coating process is possible in this case.

The identified synergies are based on the approach by WÖGINGER and extended by the synergy of the process compatibilities. The synergy of process capability illustrates, whether the integration of a further coating concept to a machine requires major or minor equipment changes.

4.2 Results and discussion

4.2.1 Results

In Table 1 the results of the total benefit calculation for exemplary portfolios are illustrated. It can be seen that the three coating processes achieve their highest values in the overall benefit in different portfolios of coating concepts. While slot die coating has its highest total benefit in the first portfolio, spray and gravure coating achieve this in portfolio two. This is due to the implementation of two-sided coating in slot die coating for the CCM concepts. Spray coating can be identified as the coating process with the lowest priority. This is mainly due to the long process time, which is still disadvantageously compared to roll-to-roll processes. Thus, slot die coating was identified as the best coating process for the use case. The concept combination of CCM PEMFC, CCM PEMEL and Decal PEMFC was identified as the best process portfolio.

Table 1: Overview results of the total Benefit

Portfolio	Spray coating	Slot die coating	Gravure coating
CCM PEMFC CCM PEMEL Decal PEMFC	18,75	27,21	23,90
Decal PEMFC Decal PEMEL CCM PEMFC	19,43	26,51	25,14

4.2.2 Critical reflection and visualization of synergies on product portfolios

A benefit coefficient that does not consider synergies is introduced to visualize the impact of synergies on the overall result. It is calculated by solely taking the amount of direct benefit values into account. The benefit coefficient and the synergy coefficient are shown in the following table for selected portfolios (see Table 2).

Table 2: Overview synergy and benefit coefficient

	Portfolio 1			Portfolio 2		
Coefficient	CCM PEMFC	Decal PEMEL	PTE PEMEL	Decal PEMFC	Decal PEMEL	PTE PEMEL

Synergy coefficient	0,43	0,22	0,35	0,42	0,44	0,14
Benefit coefficient	0,37	0,32	0,31	0,36	0,33	0,31

It is noticeable that the rankings of the components change in their prioritizations. While in the second portfolio, taking synergies into account, the Decal PEMEL components are to be prioritized. This balance shifts towards Decal PEMFC without taking synergies into account. In addition, while synergies are considered, a clearer distribution of priorities can be seen compared to the direct benefit without considering synergies.

In Table 3 the total benefits of the two portfolios with and without taking the synergies into account are illustrated. For the later, s_n equals zero in Formula (2). It can be seen that the ranking of the two portfolios changes in their overall benefits. While portfolio 2 is just preferred to portfolio 1 when synergies are considered, this ranking shifts without the consideration of synergies.

Table 3: Total benefit with and without taking Synergies into account

	Portfolio 1	Portfolio 2
Taking Synergies into account	23,60	23,62
Without taking Synergies into account	23,62	23,31

5. Conclusion

For PEMFC and PEMEL production competitiveness, a reduction of production costs is necessary. One cost potential can be exploited by combining and utilizing potential synergies between PEMFC and PEMEL production. As a result, a methodology was developed to evaluate different combinations of coating processes, taking the synergies into account. The result of the methodology is the overall benefit of the considered production process portfolio, which allows a ranking of different portfolios in relation to each other.

The evaluation of the processes is followed by the identification of synergies between the components. In this paper, synergy categories were defined and realization probabilities related to the occurrence of the synergy effects were introduced. However, the weighting of the synergies was not considered in order to be able to simplify the comparison of synergies with each other. Thus, further research is needed to develop a methodology for weighting the synergies independence of a dedicated use-case. However, it is important to ensure that the weights are determined and calculated systematically in order to avoid inconsistencies in the methodology.

The calculation of the synergy coefficients is based on the synergy identification. Synergy coefficients are calculated using the ANP approach by comparing the components of a portfolio in pairs. Thus, coefficients result that prioritize the components in the associated component portfolio. By normalizing the coefficients to one, the value is solely related to the synergy consideration of the respective portfolio. Values of the quantified synergies between components of other portfolios is not considered in the calculation of the synergy coefficients. Thus, a systematic approach is further needed that enables the comparison of synergy coefficients of different portfolios.

Furthermore, although the influence of the synergistic effect on the prioritization and selection of the portfolios was illustrated, the utilization of this effect was not validated. Thus, further research effort has to be conducted in the validation of the synergetic effects. The methodology is based on an initial evaluation of the processes to be compared. However, the framework of the evaluation is based on subjective assumptions and the required data sets for the production processes as well as the evaluation of synergies.

Thus, as a further research activity, the quality of the methodology has to be validated with real and uniform data.

6. Acknowledgements

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8. Biography

Heiner Hans Heimes studied mechanical engineering with a focus on production engineering at RWTH Aachen University. From 2015 to 2019, he was head of the Electromobility Laboratory (eLab) of RWTH Aachen University and chief engineer of the newly established chair “Production Engineering of E-Mobility Components” (PEM). Since 2019, Dr.-Ing. Heimes has held the role of executive engineer of the PEM facility.

Achim Kampker is head of the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University and known for his co-development of the “StreetScooter” electric vehicle. Kampker also devotes himself to numerous projects. These include his commitment to the “Expert Group Transformation of the Automotive Industry” (ETA) of the Federal Ministry for Economic Affairs and Climate Action (BMWK) and in the “Expert Council on Electric Mobility” of the state government of North Rhine-Westphalia.

Mario Kehrer studied electrical engineering and information technology at Karlsruhe Institute of Technology (KIT). In 2017 he joined the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University. There, Kehrer initially acted as a research assistant and later as a group leader in the Battery Engineering and Safety group. Since 2021, he is chief engineer of the Fuel Cell and Electrification Engineering division.

Sebastian Hagedorn studied mechanical engineering with a focus on production engineering at RWTH Aachen University. After joining the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University in 2019, Hagedorn became the leader of the Fuel Cell group in 2021. He is focusing his research on the adaption of process innovations in the process chain for Fuel Cell stack and system production.

Niels Hinrichs studied mechanical engineering with a focus on energy and process engineering at Ruhr-University Bochum. After working for an energy supplier in the field of gas grid technology for five years, Hinrichs joined the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University in 2021. He is researching Fuel Cell technology from a production engineering perspective against the background of automotive applications.

Tobias Pfeifer is pursuing his Master of Science in energy engineering at RWTH Aachen University and successfully completed his Bachelor of Science in Mechanical Engineering in 2022. Since 2022 he has been working as a research assistant at the institute "Production Engineering of E-Mobility Components" (PEM).